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A Summary of the AMS (American Meteorological Society) Workshop Held in Keystone, Colorado 17-20 May 1983 (Journal Version)

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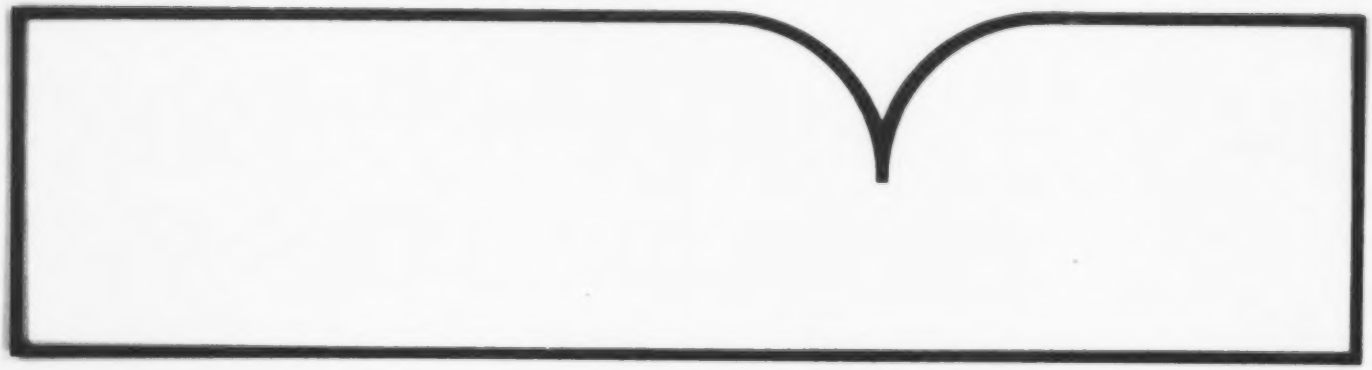

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16. ABSTRACT

This article summarizes the contributions of participants attending a workshop convened under the direction of the AMS Steering Committee for the EPA Cooperative Agreement on Air Quality Modeling. The purpose of the workshop was to address the status of our understanding of dispersion in complex or mountainous terrain settings, with a specific focus on the ability of current technologies to predict air pollution concentrations in different terrain settings.

The participants provided a number of recommendations, both on the general use of the present science and also on seven specific areas where further research is needed in order to substantially improve our ability to reliably assess the effects of dispersion in complex terrain. These specific recommendations are accompanied by more general perspectives regarding the fundamental complexity of stratified fluid dynamics when coupled with topographic environments.

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Dispersion in Complex Terrain: A Summary of the AMS Workshop held in Keystone, Colorado, 17–20 May 1983

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Abstract

This article summarizes a workshop convened under the direction of the AMS Steering Committee for the EPA (Environmental Protection Agency) Cooperative Agreement on Air Quality Modeling. The purpose of the workshop was to address the status of our understanding of dispersion in complex or mountainous terrain settings, with a specific focus on the ability of current technologies to predict air pollution concentrations in different terrain settings. The meteorological phenomena of importance for estimating the effects of elevated plumes interacting with high terrain are described in detail. Current understanding of the problems associated with lee-side flows and valley meteorology are also addressed. The present operational status of physical and mathematical modeling capabilities is summarized in relation to various terrain configurations.

The participants provided a number of recommendations, both on the general use of the present science and also on seven specific areas where further research is needed in order to substantially improve our ability to reliably assess the effects of dispersion in complex terrain. These specific recommendations are accompanied by more-general perspectives regarding the fundamental complexity of stratified-fluid dynamics when coupled with topographic environments.

1. Introduction

The need to estimate reliably the impact of emission sources in regions of complex terrain for regulatory decision-making purposes remains as a key challenge to the meteorological community. It has been identified as an area for further study at public hearings on the EPA (Environmental Protection Agency) Air Quality Modeling Guidelines and at numerous professional society meetings and conferences. The report of the AMS Steering Committee, "Air Quality Modeling and the Clean Air Act" (American Meteorological Society, 1981), identified dispersion in regions of mountainous terrain as one of the most important areas for further research and development activities.

In July of 1979, the EPA sponsored a "Workshop on Atmospheric Dispersion Models in Complex Terrain" (Hovind et al., 1979) for purposes of developing specific recommendations with respect to the design of a multi-year program to address complex-terrain modeling problems. On this basis, the EPA subsequently began a multi-phased integrated program of field studies, physical modeling experiments, and mathematical model development (Holzworth, 1980; Schiermeier et al., 1983). The Electric Power Research Institute (EPRI), as part of their Plume Model Validation and Development (PMV&D) study (Bowne et al., 1983), has undertaken a field program which also includes experiments in complex terrain. The Department of Energy's (DOE) Atmospheric Studies in Complex Terrain (ASCOT) program (Gudiksen and Dickerson, 1983) has been investigating the problem from the perspective of energy-development needs including geothermal power and oil shale. Although none of these large research efforts is completed, they are at the stage where considerable field and laboratory experience has been gained. Also, a number of mathematical model development and evaluation activities have been pursued and findings from these experiences are rapidly becoming available (Egan, 1984; Schiermeier, 1984). For these reasons, the AMS Steering Committee for the EPA Cooperative Agreement decided that it would be appropriate to review the progress made in this field and to encourage a discussion about what has been learned, what the implications are to present practice in dispersion modeling, and what these experiences might suggest with respect to possible augmentations to current research efforts.

To achieve these objectives, the AMS Workshop on Dispersion in Complex Terrain was organized and conducted. The specific purpose was to provide a forum for the exchange of technical information on atmospheric dispersion processes in mountainous terrain and the relationship of this information to the modeling of air-quality concentrations in terrain settings. A specific focus for the workshop was to provide scientific information on the capability of current complex-terrain modeling technologies for use in the activities of the EPA. The workshop's agenda emphasized measurements and observational data at the beginning to focus attention on the information obtained from recent field studies and on the importance of understanding the meteorological phenomena for model development.

Following presentations on observed phenomena, the workshop proceeded to foster discussions focusing on modeling techniques, both physical and mathematical. These topics were divided into three areas of flow field, physical,

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and "regulatory" modeling. The final sessions of the workshop involved the identification of areas needing further information, and recommendations to the technical and regulatory community at large regarding how to achieve future needs.

This article summarizes the workshop report[3] (Egan, 1985) and presents the conclusions made regarding the state of the science of dispersion modeling in complex terrain, recommendations made on the use of the science in applications, and recommendations on future research needs.

2. Phenomena of importance

In this section, meteorological or flow phenomena that are of special importance to the problem of estimating the air-quality impact of sources located in or near complex terrain are described.

a. Plume interaction with windward-facing terrain features

1) *Flow parameters affecting plume trajectories*

If a stack is located near a hill that is taller than the stack, the highest concentrations to be expected in the area are often on the hillside when the airflow is from the stack toward the hill. These high concentrations would be expected either by direct plume impingement during certain stable conditions, or by near misses as the streamlines pass close to the hill during other stable, neutral, or unstable conditions.

The presence of mountainous terrain has several effects on the flow upwind of and above the obstacles. Terrain acts to distort the flow field causing deflections, accelerations, or decelerations of the flow, and associated contractions or expansions of "stream tubes" of air. It also acts to alter the structure of turbulence within the region of flow near the surface. The dynamics of the flow field upstream of a hill depend critically on the wind speed and on ambient density (or temperature) stratification. In stable conditions, the effect of these variables can be characterized by a Froude number, Fr, given by

$$\mathrm{Fr} = U/Nh \tag{1}$$

where U is a characteristic wind speed for the upstream flow; N is the Brunt–Vaisala frequency given by

$$N = [-(g/\rho)(\partial\rho/\partial z)]^{1/2}; \tag{2}$$

g is the gravitational acceleration; ρ is the air density; and h is the hill height. Moderate to neutral stability includes the range $1 < \mathrm{Fr} < \infty$, whereas strongly stable conditions encompass the range $0 < \mathrm{Fr} < 1$.

One of the outstanding features of strongly stable flow about three-dimensional hills is the passage of fluid around the hill in essentially horizontal planes below some height, H_c, which depends on the stratification (characterized by Froude number). Above this height, fluid passes both over and around the hill. The height H_c is commonly called the "critical height" or "dividing-streamline height."

For ideal two-dimensional ridges or very long finite ridges, the fluid can be blocked (i.e., effectively become stagnant) ahead of the obstacle. For these geometries, a well-accepted formula for the dividing-streamline height does not yet exist. In addition, there is ambiguity about the upstream extent of this blocked region and its variation in depth with upstream distance.

2) *Dispersion in strongly stratified flow*

Strongly stratified flow below H_c has insufficient kinetic energy to pass over a hillcrest and, neglecting wind-shear effects, such flows can be considered essentially horizontal as they pass around a hill. When a plume lies directly along the stagnation streamline, the plume will impinge on the hill.

Along the stagnation streamline, flow diverges as it approaches the hill. Hunt et al. (1979) show that the large increase in the crosswind-dispersion coefficient, σ_y, caused by diverging streamlines, is associated with a decrease in local wind speed, U, as the stagnation point is approached, and that at the stagnation point, $\sigma_y U$ is approximately the same as it would have been in the absence of the hill. These arguments suggest that the concentration at the stagnation point is approximately equal to that which would occur in the plume without the hill.

3) *Experimental evidence of flow structure*

Snyder et al. (1982) have demonstrated the validity of the H_c concept using laboratory simulations under stably stratified conditions. These tests were made at the EPA Fluid Modeling Facility at Research Triangle Park, N.C., and in the stratified wind tunnel at the Japan Environment Agency. The concept of H_c was examined for bell-shaped hills, a cone and

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Members of the AMS Steering Committee for the EPA Cooperative Agreement (denoted by *), especially Fred White, Chairman of the Steering Committee, and Douglas Fox provided special assistance in establishing the workshop.

hemisphere, triangular ridges, vertical fences, and for a scale model of Cinder Cone Butte as shown in Fig. 1. Dye streamers qualitatively corroborated the theory that plumes released below H_c tended to impinge upon and pass around the sides of the target hill and that plumes released above H_c tended to pass over the hillcrest.

The EPA-sponsored Small Hill Impingement Studies, conducted at Cinder Cone Butte near Boise, Idaho, and at Hogback Ridge near Farmington, N. Mex. (Lavery et al., 1983), have also shown that H_c discriminates between the flow regimes for both an isolated axisymmetric hill (Cinder Cone Butte) and a two-dimensional ridge (Hogback Ridge). Photographs of oil-fog plumes along with tracer ground-level concentration patterns clearly distinguished between the horizontal flow and the flow lifted over the hills. Field experiment verification is still needed to confirm the validity and applicability of the dividing-streamline concept for terrain features greater than a few hundred meters in height.

4) *Flow over terrain during neutral conditions*

It is generally accepted that the first-order effects of terrain on altering the flow on the windward face during neutral conditions can be estimated using modifications to potential-flow theory. For regulatory applications, a practical approach involves the superpositioning of Gaussian plume spread onto trajectories determined by potential-flow approximations. Neutral conditions often are associated with high wind speeds and synoptically persistent meteorological conditions. Thus, neutral conditions can be of importance to the maintenance of 24-hour average ambient air-quality standards or prevention of significant deterioration (PSD) increments, especially where channeling effects of terrain features are important.

5) *Dispersion during unstable conditions*

For most regulatory applications, "worst-case" conditions for sources close to high terrain are expected to occur during stable or neutral conditions. For this reason, phenomena during unstable conditions have not been studied in depth. Because of the differential heating of mountain slopes during daylight hours, convection effects result in sustained and significant updrafts and downdrafts. Also, fumigation of pollutant material onto hilltops in mid to late mornings has been observed to result in short durations of high concentrations. For unstable conditions, currently available models generally use the flow trajectories derived for neutral dispersion.

6) *Turbulence levels in regions of complex terrain*

In general, turbulence levels are expected to be higher over complex terrain than over level terrain for a given atmospheric stability class. These enhanced turbulence levels are most likely a result of three factors:

a) Nocturnal, radiational cooling that produces surface inversions is often coupled with very low wind speeds in level terrain and is likely to result in the generation of gravity-driven drainage flows in complex terrain.
b) Topographic alteration of flow direction and speed will result in the production of shear in all directions, which not only contributes to the production of turbulence but results in large flow meandering.
c) In complex terrain the presence of flow stratification is a key element in the production of rapid flow accelerations and decelerations, lee waves, and rotors, which tend to produce shearing motions and regions of flow reversal.

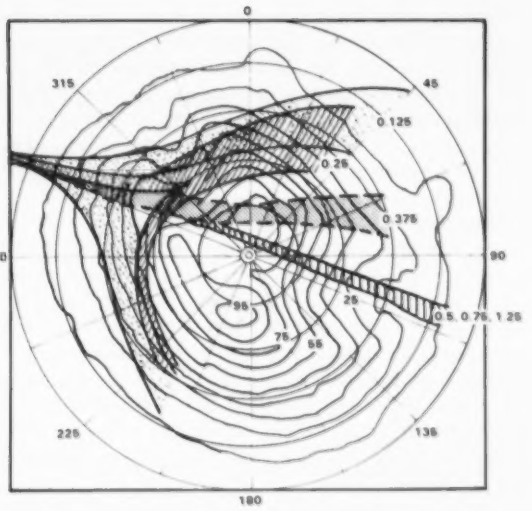

FIG. 1. Composite estimates of plume paths based on towing-tank simulations of Cinder Cone Butte model. Decimal values indicate release heights in proportion to hill height.

Lateral turbulence levels in complex terrain are generally enhanced to a greater extent than vertical turbulence. Observations of smoke-plume meandering and uplifting are reasons cited to justify an increase in horizontal dispersion rates. When the atmosphere is stably stratified, generalizations are more difficult. Air parcels downwind of a ridge may be dispersed upward (or even upwind) by rotors or other eddy motions associated with lee-side phenomena. Also under stable conditions, ridge-shaped terrain features can contribute to large-scale stagnation of the air flow in lower upwind regions, resulting in very low winds with little net transport of pollutant material into or out of the region.

b. Plume interaction with lee sides of terrain features

Fluid modeling shows that high concentrations can also be expected for certain meteorological conditions on back-facing or leeward slopes of terrain features downwind of a source. Field measurements are uncommon for these situations because regulatory requirements have generally focused on gaining information on the upwind-facing slopes nearest to a pollution source.

1) *Lee-side flow during neutral conditions*

Simple flow models are inadequate for predicting wake effects in the lee of terrain features, even for hills of moderate slope. Snyder (1983) summarized a variety of idealized neutral-flow wind-tunnel studies in which plumes from stacks located both upwind and downwind of various terrain shapes produced ground-level concentrations on or downwind of the obstacle many times higher than would be expected if the terrain were not present.

Two lee-side phenomena were observed to produce the high concentrations. One was downwind of a relatively steep hill where the flow separated steadily near the top of the lee side and reattached on the surface downwind of the base. In

this case, pollutants from sources located on the separation/reattachment streamline were advected directly to the ground, producing very large terrain-amplification factors. The other case was downwind of a hill of moderate slope where the flow separated intermittently. Pollutants downwind of this hill were thus subjected to very small mean transport speeds and very large turbulence intensities. This resulted in rapid diffusion of plumes directly to the surface.

2) *Stratified flow in lee of hills*

Under strongly stratified flows, effluents released below the dividing-streamline height on the lee sides of hills have been observed to be recirculated to the hill surface. Whereas instantaneous concentrations from downwind sources are observed to be considerably lower than impingement concentrations from upwind sources, long-term average concentrations from downwind sources may be larger because the wind meander will significantly reduce time-averaged impingement concentrations, but not the lee-side concentrations.

c. Dispersion of pollutants in valley situations

The processes identified as important to valley situations include nocturnal drainage flows, persistent low wind speed—stable flows, fumigation, and flow channeling by valley sidewalls, as depicted schematically in Fig. 2.

1) *Shallow valleys*

Shallow valleys were defined as those where an effluent plume of interest is significantly higher than the terrain features. Under these conditions, the plume is cut off from the valley boundary layer during stable conditions and reacts in a manner analogous to a plume over flat terrain, except that the trajectory of the plume may be steered somewhat by the valley orientation.

2) *Deep, draining valleys*

Some early, important research studies concentrated directly on valley meteorology and air pollution issues (e.g., Hewson and Gill, 1944). An improved understanding of valley nocturnal drainage flows is now becoming available from the DOE ASCOT program (Gudiksen and Dickerson, 1983). Other work has focused on the breakup of nocturnal temperature inversions in deep valleys (Whiteman, 1982) and has led to a model of air-pollution concentrations produced on the valley floor and sidewalls due to postsunrise fumigations of elevated nocturnal plumes.

3) *Closed valleys*

Certain valleys with weak or obstructed outflow have been characterized as trapping valleys, in contrast with draining valleys with vigorous outflow. The accumulation of cool air draining from the sides of the trapping valleys will build up a deep stable layer during nighttime hours that is capped by a stronger inversion at the interface with the above-valley air. Pollution plumes emitted into this domain are likely to be confined within this temperature structure and the valley sidewalls.

In addition to diurnal trapping regimes, certain synoptic conditions produce stagnation episodes. High-pressure systems characterized by low wind speeds, clear or foggy skies, subsidence inversions, and nocturnally-produced ground-level inversions, may exist for four- to five-day periods. During these episodes, additional emissions are not compensated by flushing so that air quality continually degrades.

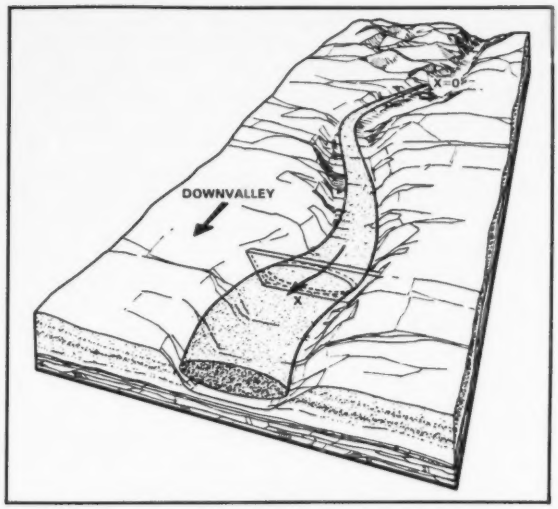

FIG. 2. Stable transport and diffusion of a pollutant plume as channeled by valley sidewalls.

d. Convective circulations in complex terrain

In flat terrain, convective flows frequently lead to the fumigation of pollutants trapped aloft or the early downwash of a looping plume, resulting in high ground-level concentrations. Convective flows developing over hills, ridges, or more-complicated terrain may significantly alter streamline patterns, separation and stagnation locations, and hill wake turbulence. It is possible that nonhomogeneous radiative heating caused by slope orientation could result in different convective scales than commonly associated with horizontal terrain. These perturbed spatial and temporal scales could result in worst-case ground-level concentrations from lee-side impingement, sudden subsidence, or downdrafts.

3. Physical modeling capabilities

The report of the 1979 EPA Workshop on Complex Terrain (Hovind et al., 1979) has a fairly detailed discussion on the background and similarity criteria for physical modeling in mountainous terrain, including a discussion of the relative merits of wind-tunnel and towing-tank simulations. In one of two EPA guideline documents, Snyder (1981) described the fundamental principles, practical applications, and hardware associated with physically modeling atmospheric dispersion. In the other, Huber (1981) specified the necessary elements of a physical modeling study for assessing the stack height required so that a plume is not adversely affected by wakes and eddies of nearby terrain (or buildings).

Since the promulgation of the stack-height regulation in 1979, a number of physical modeling studies have been conducted to evaluate the effect of terrain wakes and eddies on dispersion. These assessments have demonstrated that physical modeling can be used in a regulatory environment to define good-engineering-practice stack heights, and to assess

concentrations in complex terrain for the following situations: 1) plumes impinging on elevated terrain under neutral and stable stratifications; 2) plumes affected by the wakes and eddies of upwind terrain; and 3) plumes released in deep valleys under stable nighttime conditions.

4. Mathematical modeling capabilities

One of the more-important effects of complex terrain on plume transport and diffusion is the modification of the ambient flow field. Flow-field assumptions in existing diffusion models for regulatory applications are quite elementary. For example, diffusion models for computing concentrations on the windward slope of isolated hills assume that the same horizontal velocity exists everywhere, upstream as well as over the crest of the hill, in contrast to the streamline deformation and flow speedup that actually occur. Some of these models attempt to account for the closer passage of streamlines to elevated terrain and associated deformation of plumes by using a "terrain correction" factor, but these models ignore many details of the corresponding velocity changes and deformation effects on plume spread.

a. Current EPA recommended models

The EPA has not yet established a guideline model for use in complex terrain settings where plume heights are expected to be below the height of nearby terrain. However, the EPA does recommend the Valley, COMPLEX I, and sometimes COMPLEX II models for use as conservative screening techniques for these situations. Research on the development of a refined model is currently underway (Lavery et al., 1983).

b. Windward flow modeling about isolated hills

The earlier discussions of meteorological phenomena of importance addressed some of the major effects of hills on perturbing an airstream, i.e., streamline convergence and divergence and associated fluid acceleration and deceleration. Modeling techniques to describe these effects are all based on inviscid flow but consider two stratification regimes, neutral/unstable and stable.

For neutral/unstable conditions, potential flow is a useful concept for flow speedup, and is confirmed with field and wind-tunnel measurements. For stably stratified flow about three-dimensional hills, modelers commonly consider two stratification regimes: moderately to weakly stable ($Fr > 1$) and strongly stable ($Fr < 1$).

Models for stratified conditions, when implemented for regulatory applications, will require more-detailed meteorological input data than are generally available. Specifically, knowledge of the temperature and velocity structure as a function of height from the surface to above the terrain features will be required.

c. Mesoscale flow models

The discussion of mesoscale models considered flow models which may be applied in complex terrain for distance scales on the order of 50 km. Major breakthroughs have been achieved in recent years because of improved high-speed computer systems and more-efficient numerical schemes. Concurrently, there has been development of improved flow models, thus making it feasible to use these models for applications in a variety of complex situations. However, there is a need for additional model-evaluation studies to compare the flow fields generated by the models with actual observations.

d. Land- and sea-breeze interaction with complex topography

There has been considerable investigation of land and sea breezes over flat terrain; however, the interaction of these circulations with complex terrain along and inland from the coast has not been well investigated. McRae et al. (1981) have documented the movement of pollution offshore in the land breeze, its fumigation down to the surface layers, and its subsequent movement back onshore. This recirculation of pollution, which can occur for several days at a time in the Los Angeles basin, can result in aged pollutant plumes with high concentrations of secondary pollutants. In other investigations, numerical studies have demonstrated that coastal breezes in complex terrain are not simply a superposition of land and sea breezes over flat terrain combined with mountain/valley circulations in complex terrain.

e. Slope and mountain/valley flow modeling

Defant's (1951) descriptive model of slope and mountain/valley flows, while rudimentary, provides practical guidance for understanding thermally driven circulations in well-defined valleys. According to Defant, nocturnal shallow downslope flows on the valley sidewalls produce a deep pooling of cool air in the valley. If there are variations in the valley depth or width, an along-valley axis flow will develop which can be quite deep depending on the depth of the pool of cool air. More-recent efforts have addressed three-dimensional aspects, interactions with synoptic winds, and the turbulent structure.

5. Recommendations

A number of recommendations evolved from the workshop. These included statements regarding current research efforts and the use of current technology, identification of specific near-term research needs (which presumably could be accomplished in the near term), and suggestions regarding longer-term research needs. Some of these latter suggestions may well relate to other applications of geophysical fluid dynamics. The recommendations are organized into two categories relating to recommendations on the use of the science and on future research needs.

a. Use of the science

1) *Comments on current research efforts*

There seemed to be a consensus among the workshop participants that the research approach taken over the past several years with a focus on gathering more field data on transport and diffusion processes in complex terrain settings was appropriate. The need for large efforts to gather field data was strongly recommended at previous workshops on this topic

(e.g., EPA Workshop on Atmospheric Dispersion Models in Complex Terrain [Hovind et al., 1979]; DOE Workshop on Research Needs for Atmospheric Transport and Diffusion in Complex Terrain [Barr et al., 1977]). The research programs of the EPA, DOE, and EPRI have been very responsive to these needs.

The increased use of wind tunnels and water channels in applying physical modeling techniques to study flow phenomena was also supported by the participants. Conducting scale model tests in parallel with full-scale field experiments performed in complex terrain was viewed as providing an excellent methodology to understand the effects of physical scale on the phenomena of concern and to investigate systematically the effects of changes of dispersion patterns with flow conditions.

2) *Need to quantify uncertainties in model predictions*

One of the recurring issues surfacing at this workshop was the need for modelers to incorporate uncertainty of predictions into the process of using models. The group recognized the regulatory application needs of having decisions made on the basis of certainty and on the basis of computations made for both short and long averaging times and for infrequent events. An admonition to include uncertainty into the modeling evolves from the fact that the flow over complex terrain, like any other atmospheric flow, is turbulent in most regions at most times, resulting in uncertainty in the prediction of its behavior.

The amount of information required to quantify uncertainty is greater than that needed to estimate "mean" values since uncertainties of all the various input values and parameters need to be assessed. Such effects of uncertainty in input data and parameters can be studied with physical models where a degree of control of variables with time can be maintained.

This recommendation is also supportive of pursuits of higher-order closure modeling, which includes consideration of higher statistical moments of distributions, and of large-eddy simulation modeling wherein uncertainty can be quantified by interpretation of output results of multiple simulations.

3) *Meteorological input for complex-terrain models*

An underlying concept in the field of dispersion modeling is that one cannot expect a dispersion model to perform well without appropriate input data. Generally, *appropriate* is interpreted as being of good quality, being representative of the flow field of interest, and providing reliable information on the flow parameters of importance.

The set of meteorological data collected must be representative for the site of the source and the probable paths of pollution diffusion, including those paths which are highly repeatable and those that are expected to produce the highest levels of ground-level impact for the time periods that have regulated pollution standards.

4) *Suggestions on improving present screening models*

For impingement on high terrain, the group recognized the importance of screening models, as applied by regulatory agencies, to eliminate the need for detailed assessments for facilities having minor ambient air impacts. A screening model was defined in this context as a conservative model which can be used without any meteorological data, e.g., worst-case meteorological assumptions are made. Worst-case Valley (Burt, 1977) is the present EPA screening model for terrain higher than a source height and assumes a specific wind speed, a specific duration of wind direction, specified temperature profiles and dispersion rates, and arbitrary "miss" distances for plume paths. The group felt that because of concerns over the arbitrary and elementary nature of the assumptions already in Valley, that it would not provide a good basis for improvement. It was felt that better screening models could be developed by a two-fold effort:

a) Examine existing data available from ambient air quality or tracer measurements for a variety of sources in terrain settings to see if uniformly conservative screening algorithms could be developed on the basis of comparing peak observed and predicted concentrations.
b) Develop screening techniques that are consistently conservative. That is, develop methods which would not result in biases in the decision making depending upon differences of source-topographic situations (e.g., biased against sources located close to terrain versus farther from terrain). The degree of overprediction expected from such models should be quantified.

5) *Suggestions on use of physical modeling techniques*

The advances made in developing laboratory techniques and in understanding the limits of applicability of physical modeling techniques suggest that increased reliance be placed on their use. Application of these techniques should be considered for those situations where they are appropriate. Fluid modeling could be used to estimate the maximum short-term average concentrations under plume impingement conditions as a function of hill Froude number, stack height, and stack location, or to estimate the short-term concentrations due to terrain wake or cavity effects.

b. Future research and development needs

The workshop attendees elected to identify research needs to resolve problems of predicting ground-level concentrations of air pollutants in complex topography. These problems are associated with our ability to reliably estimate the highest concentration values that can result, and resolution requires an increased understanding of the physical processes that contribute to these high values.

The participants focused on seven problems with overlapping research needs. Table 1 lists the topics and summarizes status considerations. The ordering of tasks does not necessarily imply priority. A brief synopsis of the issues for each of the tasks is provided below.

1) *Stable plume terrain impingement*

Physical modeling and field studies have established that in stable flows a critical elevation exists that differentiates the flow that goes around a hill from the flow that goes up and over a hill. In combination with information on plume height and dimensions, better estimates of the location and magnitude of ground-level concentrations can be made. Field studies should now be directed toward establishing the validity of this concept in larger-scale and more-complex (less-idealized) terrain situations.

2) *Lee-side terrain effects*

Laboratory modeling of both neutral and stable flows over

TABLE 1. Recommended future research topics.

Topic	Hypotheses or subcomponents to be tested	Data-gathering status/needs	Physical-modeling status/needs	Mathematical-modeling status/needs
Stable plume impingement	Dividing-streamline height; scales of applicability	Data available or scheduled to be gathered	Some accomplished	Some accomplished
Effects on lee-side sources	Downwash; dividing-streamline height	Field data needed	Some accomplished	More development needed
Fumigation in complex terrain	Boundary-layer depth; turbulence characteristics	More field data needed	Modeling needed	Some accomplished
Stagnant air masses within valleys	Interaction of boundary layer with free atmosphere; sloshing and net ventilation rates	Field data not yet needed	More modeling needed	More development needed
Convective flows in complex terrain	Interaction of boundary layer with slopes	Field data not yet needed	Exploratory modeling needed	Some accomplished
Mesoscale transport	Flow-field models; boundary-layer depth	More field data needed	Not applicable	Some accomplished
Coastal/Complex terrain interface	Boundary-layer depth; data representativeness	Field data not yet needed	Modeling needed	Modeling needed

two- and three-dimensional topography has shown that elevated concentrations may be associated with a source located downwind of the terrain. A combination of theoretical and laboratory modeling is called for in an attempt to provide a sounder, physically-based understanding of these phenomena.

3) *Terrain-dependent fumigation*

The upset of a stable layer in a valley (fumigation) has been identified for many years as contributing to high ground-level concentrations. Although the physical concepts of this process are reasonably well understood, it was suggested that laboratory modeling might help to refine the understanding. Equally important is the conduct of a field experiment focused on these events.

4) *Meteorology of trapping valleys*

There exists a class of valleys that because of their orientation cause drainage winds to pool at their base forming a thick stable air mass. When circumstances are such that diurnal heating and momentum transport from above are insufficient to break this inversion, very high concentrations may occur. A combination of laboratory and field experiments was recommended to quantify the existing understanding of this situation. Studies of how to develop adequate meteorological inputs for these conditions are also needed.

5) *Convective boundary layer over complex terrain*

As a result of intensive theoretical, numerical, and physical modeling studies, as well as definitive field experiments, a fairly complete understanding of the evolution of the convective planetary boundary layer (PBL) over homogeneous terrain has been achieved. Similar systematic studies of the convective PBL over complex topography are needed. There are also no studies of the interaction between the topographically induced motions (such as in the separated cavity and wake regions) and the buoyancy-driven convective motions and their combined effects on the dispersion of pollutants in complex terrain.

6) *Mesoscale and longer-range transport and diffusion*

Although not contributing to the highest ground-level concentrations, the transport of pollutants over scales upward of 15 km to as far as 200 km is important to assess compliance with Class I PSD increments. The research necessary here requires developing a better fundamental understanding of the transport processes before significant progress can be made. Also model verification studies are needed. It is recognized that chemical transformation and removal processes become important aspects of models applied to longer-distance-transport issues. The problem of longer-range transport and diffusion in complex terrain requires the combination of a wind-field model with an appropriate diffusion scheme.

7) *Coastal/complex terrain interface*

Analysis of dispersion in coastal terrain involves further meteorological complications associated with the coupling of land/sea breezes with mountain/valley flows, discontinuities of surface temperature, and other meteorological phenomena. It was felt that although it is common for pollution sources to be located in such regions, relatively little research has been done in this topical area.

c. *Additional perspectives*

A number of more-general concerns were expressed by the group during discussions of the above research needs. There was concern that we ought to better recognize that dispersion of pollutants in complex topography is a special subset of the geophysical fluid dynamics of stratified flows. As such, under stable stratification, influences of topography can be felt well above, up, and downwind of the topography. As a result, a caution was raised regarding the extrapolation of conceptualizations which are valid and useful for simple (flat) terrain scenarios to problems in complex topography. Interactions between the physics of stratified flow and the topographic structure lead to certain natural time and space scales in the flow. In cases where such time scales are larger than the averaging time of application interest, estimates of concentration by deterministic models will contain larger uncertainties. There were references to the difficulty of developing any deterministic and generalized solution. Hence, it was suggested that the basic stochastic nature of the phe-

nomena should be accepted, and that statistical approaches be used to characterize the uncertainty.

Consideration of the more-fundamental aspects suggested that the seven problems in Table 1 depended upon an understanding of the following, more-basic items:

a) The space and time scales of the flow as a function of topography and other types of forcing or boundary conditions.
b) The depth of the planetary boundary layer in complex terrain.
c) The interaction of the planetary boundary layer with the free air above it.
d) The space and time variation of turbulence as a function of stability and topography.
e) The generalization of the dividing-streamline concept to arbitrary shapes and scales of hills.
f) The effects of radiation on the flow field in complex terrain.
g) The effects of wakes in the flow over complex topography.
h) The identification and measurement of meteorological and other data which are representative of the flows.

This list represents a very comprehensive set of basic issues stemming from the fundamental complexity of stratified-fluid dynamics, when coupled with nongeneral specific topographic environments (real topography). The associated uncertainty in the ability of simple models to simulate these processes needs to be a key concept kept very much in the forefront of any applications in complex topography.

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